Prevention of Colloidal Fouling in Crossflow Membrane Filtration: Searching for Optimal Operation Conditions: Year 2

Problem and Research Objectives

Colloidal fouling in crossflow membrane filtrations

Reverse osmosis (RO), nanofiltration (NF), ultrafiltration (UF), and microfiltration (MF) are variations of crossflow membrane filtration technology. They have steadily gained importance in environmental engineering separations over the past decade. Recent improvements in the technology—for instance, development of highly selective and permeable membranes, and efficient module designs—and several improvements in peripheral technologies have spurred widespread adaptation of these processes in environmental, chemical, pharmaceutical, and biomedical applications. The level of separation in terms of purification of the solvent, the productivity of yield measured as permeate flux, and the cost of operations have improved to the point where the application of membrane technology is now widespread in the environmental engineering industry. MF and UF, in particular, are widely used to remove suspended solids, colloidal particles, macromolecules, bacteria, and viruses from feed solutions, with particular applications as alternative, substitutional, or supplementary processes for conventional water and wastewater treatment.

A major consideration in membrane filtration operation is the cost associated with fouling of the membrane by colloidal deposition onto the membrane surface. Fouled membranes limit the permeate yield and thereby drive up the cost of operation and maintenance. Membrane fouling involves three different patterns of matter-stacking phenomena on its surface: (1) concentration polarization, (2) (followed by) colloidal cake/gel formation, (3) and aggregate cake formation (i.e., cake of retained aggregates composed of many small primary colloidal particles). All three fouling patterns constrict the permeation rate, and each effect brings out its own permeate flux decline behavior. The most typical fouling pattern that occurs during MF or UF is colloidal cake formation. A deposited cake layer contributes additional hydraulic resistance and thereby reduces the permeate flux. One of the most important governing factors of this type of fouling is cake porosity, which is mainly affected by the combined influences of transmembrane pressure, membrane resistance, solvent (typically water) viscosity, ionic strength, pH, zeta potential, temperature, and particle size. The complexity of these physical, chemical, and operational parameters often makes it difficult to attain higher flux at (possibly simultaneously) less cost. Therefore, one objective of this research is to determine optimal operational conditions by changing a few controllable parameters (among those listed) and then examining the permeate yield that results.

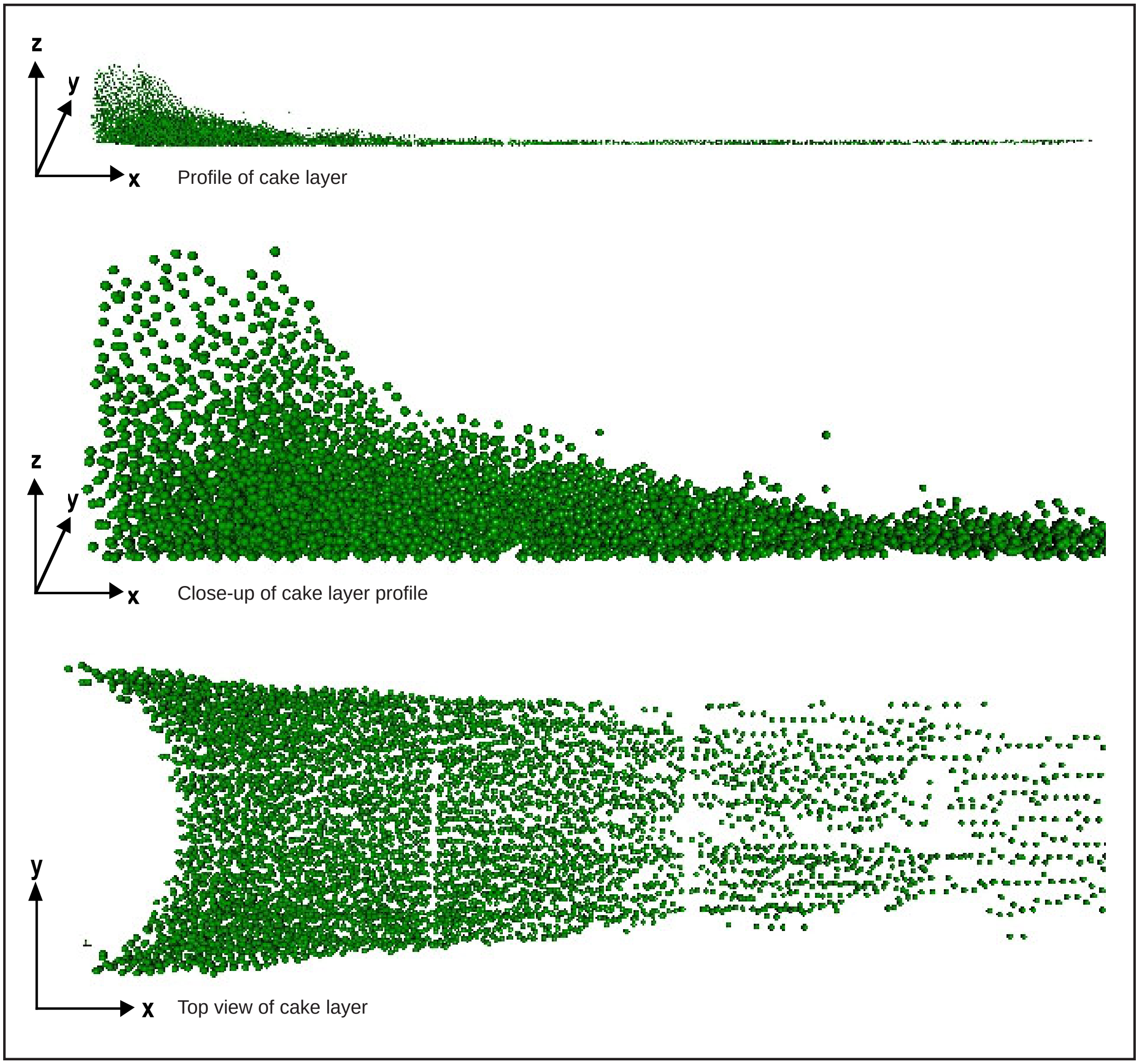
A second objective is to conduct a theoretical investigation of the aggregate cake layer, another type of cake layer that can contribute to membrane fouling, albeit in a different way. In feed water of high ionic strength, aggregation of particles readily occurs in the bulk phase, followed by the formed aggregates depositing on the membrane surface. Due to the high porosity of the aggregates (up to 0.99), this cake layer causes remarkably less flux decline than the colloidal cake layer. Inducing aggregation prior to deposition appears then to be an effective method for enhancing efficiency. Practical utilization of this phenomenon can reduce the operating cost, especially in MF/UF processes used as a pretreatment of RO/NF.

Relevance and importance to Hawaii

Desalination, a process which produces potable water from seawater or brackish water, has become increasingly important due to the paucity of freshwater, especially in the state of Hawaii. Desalination can be accomplished by using either thermal (distillation) or membrane technology. Because of the advancement of membrane technology, most water desalination plants built in the last thirty years have mainly used RO, electrodialysis, and NF. Nevertheless, the use of RO/NF membranes in water treatment processes is hindered by the presence of particulate foulants such as dissolved natural organic matter, small colloids composed of natural silica, clays, organics or biological matter, and ionic constituents, which must be removed in pretreatments of MF/UF. Therefore, this research will enhance our understanding of fouling problems in desalination processes and thus will help in the development of solutions to prevent potential fouling phenomena.

Methodology

The Monte Carlo (MC) simulation is a stochastic modeling method that is especially suitable for problems involving the dynamics of particle motion because of its capability to rigorously evaluate each discrete particle displacement. A classical method for performing MC simulations is the now-standard Metropolis method which uses



Views of cake layer developing in a long crossflow membrane channel

the energy of the system as the criterion to evaluate the acceptance or rejection of an MC step. This research adopts the Metropolis method for performing the MC simulation of the system.

The computational method employed to perform the model simulations is cluster programming by Message Passing Interface (MPI). The principle of MPI leverages the advantage of pooling together the computational power of a network of computer processors. Then the computational demands of modeling the system can be allocated among the network of processors and thus reduce a computationally intensive modeling task to manageable proportions.

We used a computer network composed of a server and many computing nodes (i.e., physical computing processors). One of the processors functions as the server while the remaining processors function as compute nodes. The server performs the tasks of organization and synchronization of the model simulation. It regulates and paces the progress of the remaining nodes which are apportioned the core computations in the model. The server provides each node with the data it requires to carry out its portion of the simulation. Data are sent from the server to each node via a “Send/Receive” communication command. Once the nodes have completed their computations for a given iteration step in the model, their results are returned to the server where they are re-organized to be sent out again for the next step. The nodes then receive the new data from the server to continue. This cycle of communications and computations is repeated throughout the simulation.

As the number of processors increase, bookkeeping of data and their communication becomes an integral component of the overall modeling scheme. Therefore, building a robust cluster-programming algorithm calls for careful evaluation of the logistical processes: data management, task organization, synchronization of nodes, and systematic communication. Improvements to the model can be achieved by ensuring better efficiency and execution of the fundamental logistics of the computing network and their interactions. The computer system used in this research is the University of Hawaii Dell cluster located on the Manoa campus.

Principal Findings and Significance

The simulation results, after 12,000 MC steps using 30 nodes, show excellent portrayal of colloidal membrane filtration at its full physical dimensions (see views of cake layer on previous page). The parameters of the model are particle size (100 μm) and applied pressure (20 psi). The crossflow velocity is 0.1 m/s. The full dimensions of the membrane system are length of 5 cm, width of 0.5 cm, and height of 2 cm. Full-scale modeling of this type has not been previously achieved in the field of colloidal membrane filtration research. Here, the model demonstrates its capability to realistically depict particle deposition in an actual membrane filtration system. Notice that the cake layer begins to form at the entrance of the channel, with a high number of particles accumulating there and then tapering off downward into the channel. The propagation of the cake layer front from the entrance downward to the exit has been theoretically proposed. So, the model results do in fact validate previous theoretical hypotheses. With the model using high-performance cluster computing currently in place, the outlook for future work is auspicious. Cake formation dynamics in colloidal membrane filtration under the influences of inter-particle interaction, hydrodynamics, and solution chemistry can now be modeled as full-scale accurate depictions.

Four journal articles and twelve conference presentations report on the research. Nine of the twelve conference presentations have already been delivered; the remaining three will be presented later this year. The principal investigator received a Certificate of Merit Award for Oral Presentation for his presentation entitled “Hydrodynamic radius of an ideal aggregate with quadratically increasing permeability: An analytic approach” at the American Chemical Society symposium in Philadelphia, Pennsylvania, in August 2004.